An Underground Laboratory in the Context of Salt Disposal Research

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ABSTRACT

Evaluating the basis of need for an underground research laboratory for salt science and engineering is imperative because of the significant commitment of time and money involved. Decades of salt repository studies, numerous experiments, and sophisticated modeling capabilities underpin the scientific database that supports safe disposal of nuclear waste in salt. The safety case for disposal of non-heat-generating waste such as transuranic waste interred at the Waste Isolation Pilot Plant is robust, with the only long-term releases to the environment projected to be by way of human intrusion. The scientific evidence also favors safe disposal of heat-generating waste. Technical evaluations for disposal of heat-generating waste in salt experienced a rather long hiatus in the United States subsequent to certification of the Waste Isolation Pilot Plant and issuance of the Nuclear Waste Policy Act Amendment that ended salt disposal research for the civilian program. Similar salt repository research in Germany was delayed by a ten-year moratorium that ended in 2010. In collaboration with German peers, the United States Department of Energy has reviewed and evaluated thermally driven processes in salt disposal and identified key technical areas in which to prioritize resources. The goal for disposal research in salt is to provide sufficient technical information to license a repository successfully. The necessity or utility of a salt underground research laboratory is to be evaluated in the context of an overall research agenda that supports a license application.

INTRODUCTION

Given the long history and encyclopedic information that underwrites salt repository science, what is the role for an underground research laboratory (URL) at this stage? Salt disposal research has followed a step-wise progression toward licensing, which is nominally represented in Figure 1. As shown in Figure 1, many of the building blocks for licensing a salt repository have been accomplished. The question pursued in this document is twofold: *Does URL testing reach a high priority in today's salt research, development and demonstration program*, and if so, *how are URL tests evaluated and prioritized*? As of today, neither the U.S.A. nor any other country has an operating URL in salt. It is a widely believed that further salt testing in a URL is not needed to address a perceived technical deficiency that would need to be answered in order to prepare a safety case for salt disposal of heat-generating high-level waste (HLW). The technical basis for salt disposal provides strong and pervasive evidence that radionuclides in a salt repository for heat-generating waste will not migrate from the disposal horizon. Current knowledge of thermal effects supports a viable concept of repository operations. The suitability of salt as a disposal medium has been recognized by national and international repository programs. Therefore, the scientific community must balance perceived need for field experiments with the recognition that a very strong scientific basis already exists for salt disposal of heat-generating waste.

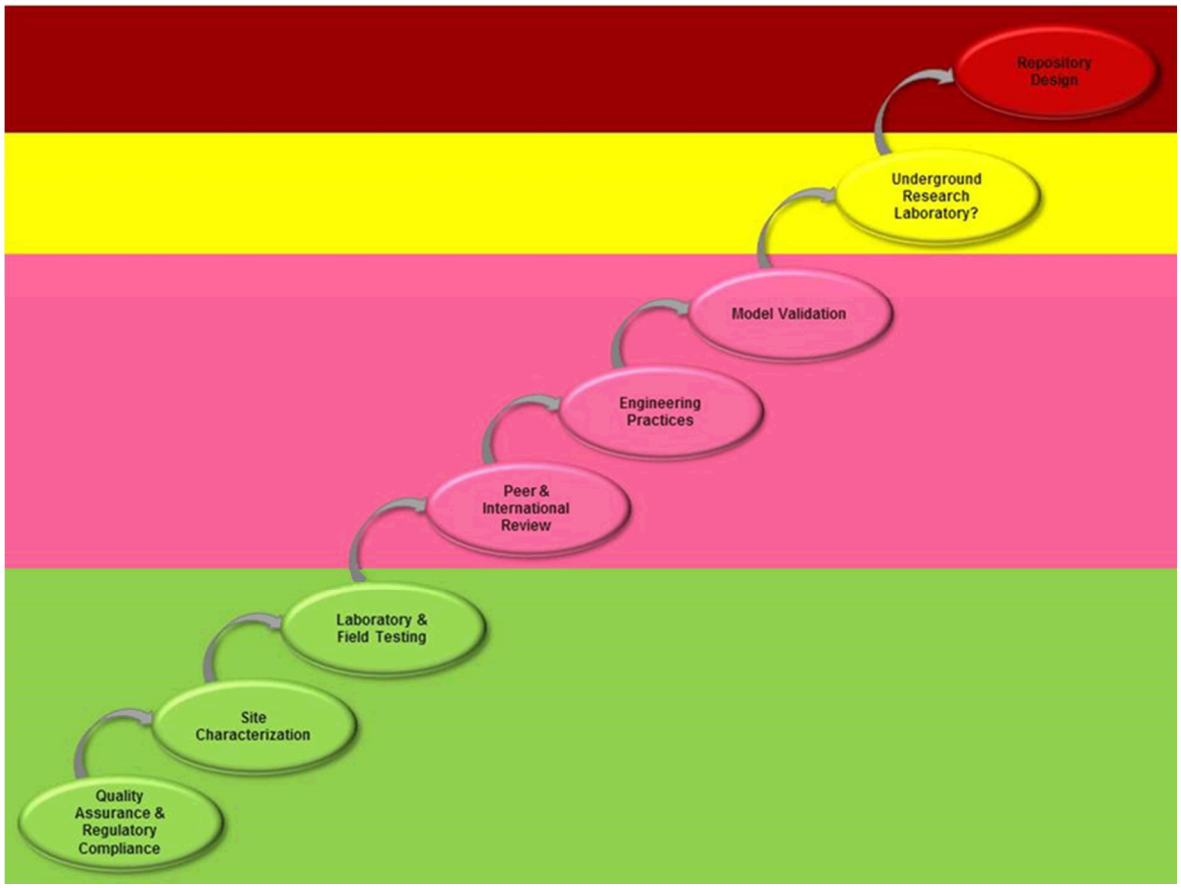

Figure 1. Progress toward a Salt Repository for Thermally Hot Waste.

This document sets forth principles as well as a methodology for evaluating proposed URL activities. Because field testing is costly, any such test will necessitate commitment of money and time. Given the large and compelling basis for successful waste isolation in salt, a choice to perform field-scale tests must be based on merit and a tangible connection to the Safety Case. Scientific investigations to support a license application are broad in scope, including laboratory tests at ambient and elevated temperature that characterize such properties as salt creep, the potential for fracture damage and its mitigation, permeability functionality of seal system components, brine accessibility via induced damage, chemical conditions in the disposal environment, and a host of other primary properties pertaining to performance assessment. The general goals for any future site characterization and laboratory or field investigations should be to build upon earlier work to reduce uncertainty and to enhance the safety basis for salt disposal. This document briefly discusses salt characteristics and modeling pertaining to disposal of heat-generating waste. The intent is to provide a status of the U.S. national effort and discuss how an underground research laboratory fits into that path forward.

If salt repository research groups are to undertake a commitment to establish an underground research laboratory, such action will involve a great obligation of scientific resources and money. Given the well-established scientific basis for salt disposal, considerations for testing underground should include scientific rigor and transparent evaluation, implemented with formality, to establish merit and priority. This paper describes a review process (Framework) to identify, justi-

fy, prioritize, and implement appropriate URL research, development, and demonstration to advance the technical basis for salt disposal.

In whole, this document provides context for an underground research laboratory in salt within a focused salt repository research and development program. Guidelines outline a process for review and prioritization of large-scale science underground testing. Implementation principles include analysis and justification for generic testing or demonstration activities that meaningfully address technical issues in a transparent and credible manner. Implementation of demonstration and confirmation activities, integrated with other beneficial uses, would help establish the expected precondition for public and political acceptance of salt disposal of heat-generating nuclear waste.

DISCUSSION

In-depth explanation of salt attributes for permanent disposal of HLW can be found in Hansen and Leigh [1] and on the Sandia website for U.S./German collaboration [2]. A brief review these characteristics will help clarify the basis for advancing salt repository research. Long-term behavior of salt, fundamental to repository applications, requires detailed understanding of deformational processes, such that extrapolation can be made beyond human experience. The scale of research ranges from a microstructural level to full-scale demonstration in the underground. Under most conditions involving elevated temperature and modest confining pressure, salt deforms plastically. The phenomenon of flow without fracture (creep) is one of the primary attributes of salt as a disposal medium.

Advanced constitutive models in the U.S. and Europe have been used to describe phenomena associated salt deformation and their dependence on different fundamental mechanisms. These constitutive models are often expressed in elegant mathematics and are currently being benchmarked in ongoing international collaborations. This deep understanding of salt deformational properties can be validated by field tests, while models can provide direct input to URL activities. Therefore, regardless of proposed field activity, structural mechanics modeling has a role in defining the test bed.

Laboratory investigations in Germany and the U.S. have provided the background understanding of salt mechanical and thermomechanical responses to anticipated repository conditions. Temperature has a dramatic effect on salt deformation and, therefore, temperature and associated heat management are first-order concerns for disposal of heat-generating nuclear waste in salt. The importance of heat from radioactive decay depends on the effects that the induced temperature changes could have on mechanics, fluid flow, and geochemical processes within a salt formation.

Salt deformation in the laboratory and in the field can be accompanied by significant fracturing at room temperature, low confinement, and relatively high differential stress, conditions that occur near free surfaces of the repository openings. Salt, therefore, exhibits brittle deformational processes near the roof, floor and ribs, but deforms by constant volume processes at depth within the rock formation. The properties that typically define the disturbed rock zone (DRZ) include: (1) fractures ranging from microscopic to readily visible scales, (2) loss of strength evidenced by rib spall, floor heave, roof degradation and collapse, and (3) increased fluid permeability via connected porosity. Characteristics of the DRZ provide boundary conditions for activities con-

ducted within excavated space. These characteristics evolve with time and deformation; however, fracture development near excavations occurs rapidly. Evidence shows that damaged salt can heal under certain conditions, which is another important phenomenon conducive to investigations in a URL.

The Joint Project III collaboration, called *Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt* started in October 2010. This project compares modeling capability for temperature influence on deformation and for sealing and healing of damaged and dilatant rock salt. The research group is in the process of benchmarking salt mechanics codes against WIPP field tests, which were conducted during site characterization. The benchmarking study on sealing and healing comprises all phenomena that result from the elastic closure of open microcracks up to the re-establishment of chemical bonding along fracture surfaces. In the constitutive models of the partners, modeling these effects is based on a description of the healing rate as function of the current dilatancy and the stress state. Differences in the models arise from differing assumptions regarding the healing boundary. This project phase comprises performance and back-calculation of specific laboratory tests as well as simulations of selected *in situ* structures. The benchmarked codes will thereafter provide analysis tools for any possible test or demonstration in a salt URL.

A salt URL could potentially host a wide assortment of tests to confirm our collective (international) knowledge on the technical basis for salt disposal. Consistent with our goals of collaboration, URL space could be used to underwrite internationally significant science and engineering, such as demonstration of sealing elements and the evolution and healing of the DRZ. An ongoing performance confirmation program would be an integral part of a license for regulatory approval of nearly any repository. Performance confirmation would also be necessary within the safety case arguments, similar to the experiences at WIPP and Yucca Mountain. Ongoing science made available by a salt URL holds the potential to reassure societal and political stakeholders. Due diligence also demands ongoing scientific research to confirm the licensing basis, even though the safety case for a salt repository is robust and well substantiated.

FRAMEWORK

The opportunity to set out a research strategy specific to salt disposal of HLW helps focus objectives, which can be justified in several ways. A test or demonstration might address specific features, events or processes (FEPS) to confirm our understanding and ability to model performance of a deep geologic repository for heat generating radioactive waste in salt. An activity might be proposed to build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods. A URL activity might be identified by consensus of international collaborations. Many test concepts pertain to design and operational practice, which embody model prediction and confirmation at full-scale. These particular objectives align with similar lists put forward by IAEA and NEA [3, 4]. Many objectives taken from the literature are intertwined and expressible in different descriptive forms. For example, *addressing FEPs* essentially means the same as *assessing performance of the repository system*. Building confidence by reducing uncertainty is a well-recognized basis for field testing. Interna-

tional collaboration is a goal and perhaps a strong justification for investing in a field activity of mutual, international interest.

Development of proposed testing activities will benefit considerably by integrating information from Performance Assessment into the planning and prioritization of science and engineering activities. The Performance Assessment methodology uses a hierarchy of upper tier requirements that drive data needs to support safety case development. This structured framework can be used to prioritize activities and transparently communicate up-to-date understanding of the repository safety case. Information within Performance Assessment calculations can readily identify the nature and potential impact of remaining uncertainties, which provides a measure of perceived benefit to be realized by testing. Fundamentally, activities to be undertaken in a salt URL would need to be justified on an objective basis.

Creation of new underground space for salt science could provide an exceptional opportunity to further advance the scientific basis for disposal of heat-generating waste in salt. Recognizing that mined space is an expensive and limited resource, this opportunity comes with a significant responsibility to use the space as strategically and cost-effectively as possible. Activities within the underground will be highly visible and carry an obligation to serve generic needs of U.S. national repository programs, international scientific interests, as well as other complementary programs. Plans for a URL must be prepared with the highest scientific rigor and address issues pertinent to safe disposal of heat-generating waste. Research must be planned in the context of the existing body of salt science.

Given the broad descriptions of objectives, how can various URL ideas be rated and evaluated? What process is available to differentiate and select URL activities? A commitment to pursue URL testing requires a structure to weigh relative merits of proposed activities. This is called a *Framework*, which basically describes a simple progression for field test development and selection.

1. Describe activity
2. Hold independent review
3. Rank and prioritize
4. Make recommendations
5. DOE select
6. DOE plan and budget

The Framework concept is quite simple: **use draft Test Plans to describe proposed URL activities and assemble a small independent review panel to evaluate merit**. Use of a draft Test Plan compels the Principal Investigator to justify the activity and demonstrate connection to the safety case. A draft Test Plan also describes parameters, specifics of measurement techniques, data quality objectives, and other information in sufficient detail that objective technical review is possible. Independence of the review panel is essential to demonstrate transparency to stakeholders and to provide DOE a recognized basis for test selection. This deliberate step is indispensable to the credibility and ultimate success of the URL. Not only does independent review help maximize utility of precious underground testing space, but it underlines the intended generic application of URL studies. The mission of the independent review panel is to critically evaluate and make recommendations regarding the overall mission and proposed research strategy for the URL. In response to the initial external review, the research strategy will be refined, leading to a

road map for usage of the underground research space. The panel could provide periodic review of technical progress and afford impartial input for future decisions.

Conclusions and recommendations of the review panel would then be considered by DOE to optimize available and potential research funding. Near-term and long-term temporal sequencing and spatial arrangement of tests in the URL could be considered, which may identify initial and chronological tests in the URL. At this stage, the DOE would be able to identify functional and operational requirements from a system-level perspective in order to sequence the proposed activities. Development of the functional and operational requirements should include discussion of the size, shape and arrangement of openings, analysis of possible test-to-test interference, sequencing and duration, power requirements, ventilation systems, data acquisition, synergistic goals and possibilities, quality assurance, records management, and other attributes of a well-considered program. These discussions should take into account potential funding sources for tests to be conducted in a salt URL, along with the differing customer expectations that may be tied to those funding sources.

Previous underground testing provides guidelines for an extensive and well documented science program. Quality Assurance procedures governing preparation of Test Plans have been used on the WIPP project for many years and several comprehensive examples exist from previous underground testing; e.g., Sandia's Nuclear Waste Management Procedure NP-20-1 covers Test Plans for field and laboratory experiments. Test Plans are reviewed and approved prior to initiation of work and describe the scientific activity in sufficient detail to allow action to be taken. Creation of a Test Plan will include objectives and describe parameters to be measured, such as deformation, temperature and stress. Data quality objectives for measurement of fundamental parameters are derived from simulations using advanced codes and models, such as thermal-structural mechanics modeling. In turn, the instrumentation and its layout, cabling, time sequencing, power, and data channels all can be developed based on thermal-structural calculations. A Test Plan should also provide a set of post-test evaluation criteria to determine how the results of a completed test might be used to inform future testing. Depending on the location of the URL, the site owner would have operational purview. A coordination group for underground operations would take action required to implement the Test Plan details.

The Framework for conduct of URL studies facilitates objective, rigorous, and transparent science. With strategic planning, investigations conducted in the underground can address a number of salt-based disposal issues while supporting generic salt studies. If undertaken with a vision toward the future, operations within a URL could become a national and international centerpiece for salt repository research. Involvement of the international community would add scientific credibility and further strengthen stakeholder confidence. Operating a URL should allow participation by the next generation of students and nuclear waste management scientists through provision of a unique laboratory for basic and applied model development, laboratory testing, and field investigations.

USE OF THE URL

There are many potential uses of a salt URL [5], so it is essential to have a process to evaluate and prioritize. Furthermore, a long-term view of URL functions is vital to assess dual-purpose

synergy, test-to-test interference, data acquisition, and infrastructure. Although a URL would focus on issues related to HLW disposal, the overall portfolio would also include repository design and operation issues that are separated from heat, such as engineered barrier construction. This section reviews some of the proposed uses of a salt URL.

The idea of salt disposal, as well as disposal in other media, was restarted after the Yucca Mountain Project was declared unworkable in 2008. Concepts to reinvigorate salt disposal investigations were also outlined at that time, including a sequence of laboratory testing, benchmark modeling, international collaboration, and field testing [6]. Several large-scale tests and demonstrations have been described in publications [5] and two specific large-scale heater experiments tests for a salt URL were developed by the Carlsbad Field Office—Salt Disposal Investigations (SDI) and Salt Defense Disposal Investigations (SDDI) [7, 8]. In addition to a series of public manuscripts describing possible tests within a salt URL, the U.S./German Workshops on Salt Research, Design and Operation examined a suite of the proposed URL activities [2, 9]. A formal, independent review—such as advocated in the Framework discussion—has not been undertaken.

At the 4th U.S./German workshop, concepts for use of the WIPP URL were discussed once again by dividing attendees into break-out groups. Several potential URL activities were reviewed, including those previously identified in the literature [5] as well as some new ideas. Workshop participants were asked to provide a high-level review and feedback concerning a sense of duration, cost, and merit among the eight potential uses. The physical phenomena (such as thermally driven creep processes or damage healing) also require relatively large scale and time-dependent evolution. In Table 1, cost is abstracted as dollar signs ($ ~ 1 million, $$$$ > 10 million) and time is estimated in year durations. The counterpart to cost and time is perceived benefit, which can be achieved at several different levels. In these high-level considerations benefits were categorized as confirmation, demonstration, validation, and new science. In tests where "new science" was advanced as the purpose, the technical merit column identifies the nature of the advancement. Of course, this review and discussion was rather cursory and a more formal and rigorous review process of URL activities would be expected in order guide development.

Table 1. High-level Review of Possible URL Activities.

Activity	Purpose	Duration (years)	Cost	Technical Merit
Single Heater	Confirmation	1-5	$$	Model validation
Large-scale Seal	Confirmation and demonstration	5	$$$	Confirmation, demonstration, and performance
SDI-Hot waste	New science	5+	$$$$	Accelerated results, model validation, demonstration
SDDI-Defense Waste	Demonstration	5	$$$$	Demonstration
Wedge Pillar	New science	N/A	N/A	Not supported
Fluid differential pressure test	New science	3	0.5$	Intact permeability in bedded salt
In situ consolidation	New science	<3	$	Consolidation data gap, permeability
Canister movement	New science	5+	$$	Model buoyancy

Most of the proposed investigations were considered expensive and of long duration. The concept of a wedge pillar was not supported because in a broad-brush it appears to be redundant to similar testing that was completed at the Asse Mine in the 1980s. Of course, these evaluations of merit are high-level perspectives and more in-depth examinations would be undertaken for proposed URL activities. These preliminary evaluations of the many potential uses for a salt URL are based upon the experience and lessons learned in the design and management of the original underground investigations program that supported the technical basis for the WIPP as well as decades of salt experimental programs undertaken in Germany. International experience in salt and other geologies provide further insights into the proper design and operation of URL research programs for maximum utility.

CONCLUSIONS

The viability of salt formations to host a nuclear waste repository has been well established. The WIPP is a transuranic waste repository in bedded salt in the U.S. Its certification was preceded by substantial laboratory and field experimental work and modeling. The German repository program produced a preliminary safety case for a repository in the Gorleben salt dome. Sufficient technical backing is therefore believed to exist to produce a license application for a salt repository if the U.S. policy is set in that direction. The salt repository program does not need a field disposal demonstration to resolve an unknown technical issue before a license application can be prepared. On the other hand, if confirmation or demonstration of performance expectations is felt to be essential for public acceptance, then it is possible that confirmation testing/disposal demonstration could be developed to address such a societal prerequisite. The use of

a salt URL could also signal that the HLW program for salt disposal is committed to performance confirmation.

Examples of field testing and engineered barrier construction further demonstrate the existing ability to seal a repository in salt. The state of international repository research, design and operation has been discussed and published in several annual workshops between U.S. and German researchers. International collaboration continues to advance the basis for salt disposal, with exceptional modeling of WIPP Rooms B&D and many new laboratory tests on WIPP salt. Within this context, the proposition of a salt URL requires justification and establishment of merit in an objective and open implementation Framework. Given the likely programmatic outlay in terms of time and money, a careful assessment of the return on investment is imperative. Therefore, a Framework for implementation is needed to guide selection of the most promising uses of underground space.

A URL in salt would provide opportunities for advancing identified U.S./German research interests and university outreach. Collaboration with Germany and other nations with salt disposal issues (The Netherlands and Poland) would help assure credibility of proposed URL activities and could promote partnering on certain ventures. No matter what activity is selected for the URL, new excavation provides a test bed for measuring evolving formation properties of salt before, during and after the openings are made. Advanced planning allows modeling prediction of deformation and changing permeability. Thus, pre-test characterization (often called a Mine-By Experiment) sets up a code validation/confirmation exercise in the process of defining test configurations.

This document provides an overview of field-scale testing in the context of the large body of information supporting salt formations as viable for disposal of heat-generating waste. Field testing almost invariably involves long times for planning, pretest preparedness, Test Plan review, readiness review, and execution. Given finite resources, consideration and selection of URL activities takes on a role proportional to its cost. Justification for field testing must be made in the context of an overall salt disposal research program.

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